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Analysis of Space Tug Operating Techniques Final Report (Study 2.4)

Volume I: Executive Summary

Prepared by
ADVANCED VEHICLE SYSTEMS DIRECTORATE

August 1972

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASw-2301

Systems Engineering Operations
THE AEROSPACE CORPORATION

35

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FINAL REPORT (STUDY 2.4)
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Volume I: Executive Summary

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FOREWORD

Study 2.4, "Analysis of Space Tug Operating Techniques," was managed by the Advanced Missions Office of the NASA Office of Manned Space Flight. Dr. J. W. Wild was the Technical Director of this study; day-to-day management was performed by Mr. R. R. Carley. Mr. R. E. Kendall was The Aerospace Corporation Study Director from study initiation until 3 April 1972. Dr. L. R. Sitney directed the Study from that date through completion.

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I. INTRODUCTION

This report summarizes the major portion of the work done on Study 2.4, "Analysis of Space Tug Operating Techniques," of Contract NASw-2301. Other tasks performed under Study 2.4 are reported in Study 2.3 final report and a supplemental report on Study 2.4. These other tasks are defined later in this section. The following tasks were considered as potential specific study tasks for Study 2.4.

- Task 1 - Impact of DOD-Unique Requirements on an ELDO-Designed Tug
- Task 2 - Utility of a Non-Autonomous DOD Tug
- Task 3 - Licensing Considerations (Of an ELDO Tug)
- Task 4 - Identification of Tug Subsystem Cost Drivers
- Task 5 - Conceptual Design and Operation of a Payload Retrieval Mechanism
- Task 6 - Conversion of MSFC Tug Point Design to NASA/DOD Multi-Purpose Tug Design
- Task 7 - Tug Technology Requirements
- Task 8 - ELDO Technology Assessment
- Task 9 - Tug Refurbishment Costs

Tasks 1 and 9 were selected for first priority, the former being limited to a review of available documentation from the ELDO Phase A Studies, the ELDO Phase A Statement of Work and DOD OOS Studies. Participation in the ELDO Tug Subsystem Design Reviews anticipated for July 1972 was planned by Aerospace as part of Task 1. This effort was not expended due to cancellation of the ELDO Subsystem Review Meetings as a result of the termination of the ELDO Tug activities. A preliminary one-month assessment of Tug refurbishment costs was made on Task 9 utilizing existing cost estimating relationships (CERs). The results were of sufficient interest to warrant an in-depth "bottoms-up" analysis of Tug refurbishment costs. A detailed study plan was then submitted to the NASA Technical Director and, following its approval, the "bottoms-up" analysis was initiated. This analysis used the total remaining study manpower.

During May 1972 a NASA review of the refurbishment effort (Task 9) resulted in the following recommendations for the remaining refurbishment effort.

Item 1 - Improve Refurbishment Estimates and Review Design Impacts

a. Define Tug fault detection methods for each Tug major system.

b. Identify test points and sensors for fault isolation of each system listed above.

c. Continue review of refurbishment man-hour estimates to assure common base for estimates and to describe unusual man-hour requirements.

d. Review tank insulation refurbishment approach.

e. Review auxiliary propulsion system refurbishment approach for possible reduction in man-hour requirements.

f. Investigate new tank design approach.

g. Clarify fuel cell refurbishment estimate.

h. Summarize the refurbishment vehicle design impacts (requirements) as determined from the refurbishment studies.

Item 2 - Establish Study Parameters to Determine Impact on Refurbishment of NASA/USAF Two Launch Site Concept

Item 3 - Refurbishment Engineering Support Requirements

a. On-site vehicle and subsystems.

b. Off-site vehicle and subsystems.

With the exception of Items 1a, 1b, and 3, these items were accomplished by the end of the study. Items 1a, 1b, and 3 were addressed at the end of the study period in a very broad sense, however, and are reported separately in Aerospace report ATR-73(7314)-2. Item 2 was not addressed to any depth due to the low (less than four flights per year) anticipated Tug traffic rate from the Western Test Range (WTR).

During the FY 1972 effort, the following Tug activities were supported jointly by Studies 2.3 and 2.4:

1. Tug Implications of Mark I/Mark II Shuttle Program

2. ELDO Phase B Cost Estimates

and are reported as part of Study 2.3, Aerospace report ATR-73(7313-01)-1. This document therefore contains only the effort expended on Task 9, Tug Refurbishment Costs.

II. STUDY OBJECTIVES

The purpose of the refurbishment study was to establish, by a "bottoms-up" analysis, the cost of maintaining the reusable third stage of the Space Transportation System, viz., the Tug. Design effects and requirements of selected components that result from the refurbishment function were to be identified. Also, areas requiring in-depth subsequent studies were to be identified. The statement of work is contained in Appendix A.

III. RELATIONSHIP TO OTHER NASA PROGRAMS

The Tug Refurbishment Cost Study was conducted from November 1971 to August 1972. During this same time period, the following major Tug-related studies were also being conducted under NASA sponsorship:

Space Tug Point Design Study - McDonnell Douglas Astronautics Co. (MDAC)

Space Tug Point Design Study - North American Rockwell

Space Tug Economics Study - Lockheed Missiles Space Co.

Space Tug Aerobraking Study - Boeing Aircraft Co.

Tug Operations and Payload Support Study (TOPS) - North American Rockwell

Space Tug Launch Site Service Study - General Dynamics/Convair

Shuttle Orbital Applications and Requirements (SOAR) - MDAC

Tug refurbishment was addressed in the two Space Tug Point Design Studies but only to the extent of Refurbishment Plans and top level preliminary cost estimates. The Space Tug Economics Study considered both expendable and reusable Tugs. Refurbishment effort was limited to the use of a range of refurbishment cost factors in the assessment of overall reusable Tug operations costs. Data generated in The Aerospace Corporation Refurbishment Cost Study were used to bound the range of refurbishment cost factors used in the LMSC Space Tug Economics Study. The Tug Aerobraking Study, and TOPS and SOAR studies were design and operations oriented, respectively, and therefore did not address the subject of refurbishment. The Space Tug Launch Site Service Study, which has as its primary objective the evaluation and identification of the major ground operations requirements and interfaces for a ground-based Tug, was initiated in July 1972 and will address the subject of Tug refurbishment operations in significant depth. The importance of additional study regarding Tug refurbishment costs is the result of its impact on overall Tug turnaround costs for a reusable vehicle. This impact was identified in The Aerospace Corporation Study 2.4 reported herein.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

A list of ground rules and assumptions were generated to cover basic design philosophy required for a refurbishable vehicle, assumptions concerning fault isolation and replacement of failed components, and the portion of Tug ground operations considered as Tug refurbishment.

A. APPROACH

A baseline vehicle was synthesized from available data obtained from both funded and in-house Tug/OOS studies. The vehicle was divided into the following eleven major areas for which basic data were generated:

1. Basic Structure
2. Meteoroid Shield
3. Tug/Payload Docking Mechanism
4. Tug/Shuttle Docking Mechanism
5. Interface Panels
6. Propellant Tanks
7. Propellant Tanks Insulation System
8. Main Propulsion System
9. Auxiliary Propulsion System
10. Electrical Power
11. Avionics

This was done by means of "Refurbishment Data Sheets" and "Refurbishment Operations Sheets." The "data sheets" contain all of the pertinent descriptive information for each of the major vehicle areas, e.g., the function of the equipment; physical characteristics, such as weight and size; an estimate of the unit cost and maturity of the equipment; expected failure modes and rates, where known; and an estimate of the cost to refurbish the piece of equipment. The "operations sheets" describe the actual tasks that are necessary to keep the equipment functioning properly, the frequency at which the tasks are performed, the hardware replaced during the tasks and an estimate of the manpower required to perform the tasks.

From the data and operations sheets, an estimate was made of the scheduled maintenance costs for each subsystem. Next, using the information available on subsystem mean time between failure, an estimate was made of the subsystem maintenance costs due to random failures. The total Tug refurbishment costs were then tabulated and the cost drivers identified. Refurbishment design effects and requirements of selected Tug systems that have a significant effect on refurbishment costs were identified. An assessment was also made of areas that are of major concern to refurbishment and which require subsequent in-depth studies.

The data used in this study came from many sources. Tug/OOS vehicle contractors were surveyed for applicable information. The NASA Tug and Air Force OOS funded studies were utilized where appropriate. Various component vendors were canvassed relative to their particular hardware. In-house specialists who have experience in past and current Air Force space programs in each of the major vehicle areas were utilized. From these sources a data base was established from which a best estimate of the cost to maintain the Tug was made.

B. GROUND RULES AND ASSUMPTIONS

The first and most important assumption made in this study is that the vehicle must be designed for ease of maintenance. All of the manpower estimates are based on the assumption that components can be easily removed and replaced in the vehicle. In addition, the vehicle should be built up of major subsystem modules so that the vehicle can be readily disassembled into its major subsystems as depicted in Figure 1.

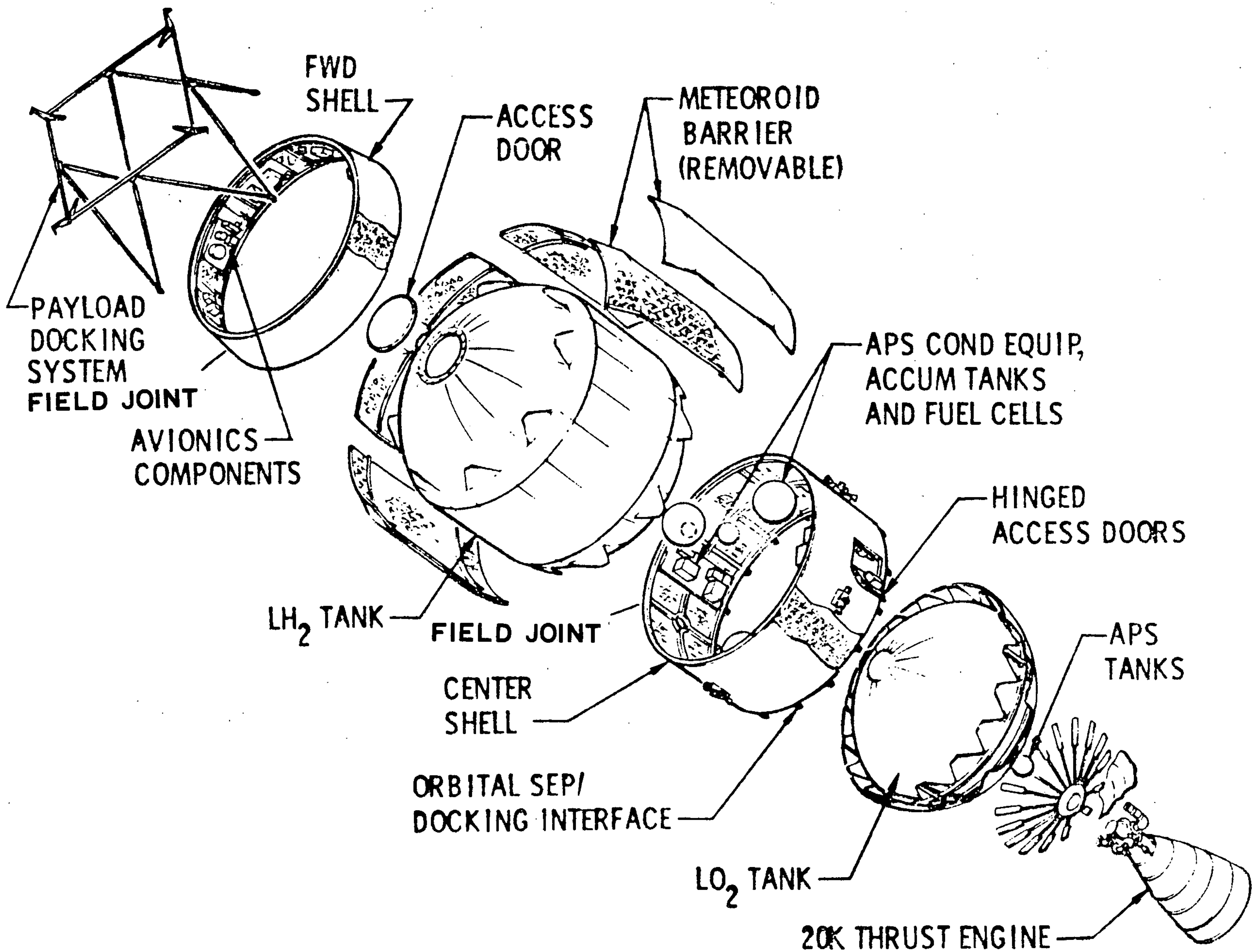

Figure 1. Design for Access and Maintenance

For the purpose of this study, it was assumed that all Tugs are successfully launched by the Shuttle, complete their mission, and are successfully returned to the launch site by the Shuttle. In-flight Tug failures are detected on board and a redundant component is used to successfully complete the mission.

The Tug system includes built-in test equipment (BITE) to the component level. Wiring and connector reliabilities are assumed to be part of the component reliability.

The baseline vehicle is composed of components/assemblies such as star trackers, computers, etc. These items are, by definition, the Line Replaceable Units (LRU) and, if they fail in flight, the Checkout and Fault Isolation (COFI) system, in conjunction with the Tug data management and software systems, automatically switch in the redundant component/assembly. When the Tug returns to the maintenance area, the failed or indicated failed component/assembly is found by inspection, post-flight tests, flight recorder data, etc., removed, replaced, checked out with regard to its own system/subsystem and then verified by a post-maintenance vehicle level test. The failed component is taken to the repair depot for refurbishment and then returned to the maintenance storeroom. The repair depot may be at the maintenance area or located off-site. For the purposes of this study, it has been assumed that this repair is costed out at a certain percentage of the unit cost, ranging from 15 percent to 60 percent depending on the item. The actual manpower identified with this effort is only that necessary for removal and replacement of the component on the vehicle. Therefore, whether or not this repair is performed on- or off-site is immaterial as far as this study is concerned. The actual tradeoffs to determine whether this repair is done off-site or on-site should be the subject of a subsequent study.

The previous paragraph implies the two assumptions that all indicated failures result in component replacement prior to the next mission and that the maintenance costs and rates reflect both real failures and false alarms.

Another important assumption concerns the portion of the actual ground turnaround operations considered to be part of Tug maintenance, i.e., that portion which occurs after the Tug has been safed and unloaded from the Shuttle and before the Tug is turned over for prelaunch operations as a "new" vehicle. The operations considered for this study are those involved with transporting the Tug to the maintenance area, analyzing the flight data, performing the pre-maintenance vehicle level test, performing the actual maintenance operations and then performing the post-maintenance vehicle level test. At this point, the vehicle is considered to be a "new" vehicle and the subsequent operations are charged to other functions. The vehicle at this time may either be put in storage for later use or sent on to the pre-launch activity area.

Only the manpower required to operate the ground equipment is considered in this study; the cost of the ground equipment itself is not addressed.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

A. VEHICLE DESCRIPTION

The vehicle used for this study was synthesized from data obtained from NASA and DOD funded Tug/OOS studies and Aerospace in-house efforts. The vehicle is an integral propulsion stage utilizing liquid hydrogen and liquid oxygen as propellants and is capable of operating either as a fully or a partially autonomous vehicle. Structural features are an integral LH_2 tank (mounted forward), an LO_2 tank (mounted aft), a meteoroid shield, an aft-conical docking and structural support ring, and a new staged combustion main engine. The vehicle is constructed of major modules for ease of maintenance.

B. REFURBISHMENT COST ESTIMATE

The baseline vehicle was divided into eleven major vehicle areas for which refurbishment costs were generated. Table 1 shows the average refurbishment cost per mission for each of these areas. Phase II and Phase III in Table 1 refer to different phases of the flight program. Phase II refers to the initial operational capability (IOC) portion of the flight program which consists of the first 20 flights after the flight test program. Phase III is the operational capability (OC) portion of the flight program and the refurbishment costs associated with this phase are for a mature vehicle. Scheduled refurbishment costs refer to the costs associated with planned maintenance and replacement. Unscheduled refurbishment costs refer to costs associated with random failures.

The average refurbishment cost for an initial operational vehicle (IOC) is $429,000 per flight as compared to $273,000 per flight for a mature vehicle (OC). The reduction in the average maintenance cost is due to a reduction in the scheduled hardware replacements and detailed inspections that are performed during IOC. The purpose of these detailed inspections is to aid in developing and determining the reusability of the various systems. In addition, the unscheduled maintenance costs in the OC phase

Table 1. Tug Refurbishment Cost Per Mission
Thousands of Dollars

	PHASE II - IOC			PHASE III - OC		
	Scheduled	Unscheduled	Total	Scheduled	Unscheduled	Total
Basic Structure	0.6	0	0.6	0.6	0	0.6
Meteoroid Shield	11.0	0	11.0	11.0	0	11.0
Tug-P/L Dock.	5.4	1.3	6.7	5.4	0.6	6.0
Tug-Shuttle Dock.	2.9	0.3	3.2	2.9	0.1	3.0
Propel. Tanks	15.5	28.5	44.0	15.5	14.3	29.8
Interface Panels	11.3	0.2	11.5	10.3	0.1	10.4
Tank Insulation	64.6	3.6	68.2	48.3	1.8	50.1
Main Prop.	36.5	34.5	71.0	19.8	17.3	37.1
Aux. Prop.	85.6	35.0	120.6	44.9	17.5	62.4
Elect. Power	30.2	4.5	34.7	27.3	2.2	29.5
Avionics	4.4	34.2	38.6	2.9	17.1	20.0
System Tests	18.7	0	18.7	12.7	0	12.7
TOTAL	286.7	142.1	428.8	201.6	71.0	272.6

represent a mature system whereas, in the IOC phase of the program, the mean time between failure (MTBF) of the various systems is assumed to be only half of its mature value for that system.

The scheduled maintenance costs represent the major portion of the total refurbishment costs, except for the avionics system, where the unscheduled maintenance costs are approximately 6 times higher than the scheduled maintenance for a mature vehicle. This is due to the maintenance philosophy assumed for the avionics system, i.e., nothing is replaced unless it fails. This philosophy is possible for the the avionics system because the system contains significant redundancies and essentially never wears out. This type of philosophy is not feasible for a system like the propellant tank insulation system or the main propulsion system where there are definite wearout modes and the systems are not redundant.

Table 2 presents the refurbishment costs for IOC and OC as a percentage of the vehicle first unit production cost. The cost for IOC is 3.91 percent and 2.49 percent for OC. These percentages are made up of five main drivers. For OC, these are in order of importance: (1) the auxiliary propulsion system, (2) the propellant tank insulation system, (3) the main propulsion system, (4) the propellant tanks, and (5) the electrical power system. In the IOC phase, the avionics system is more expensive to maintain than the electrical power system. This is a result of the relative immaturity of the system in the IOC phase of the program and the fact that almost all the cost of maintaining the avionics system is due to unscheduled maintenance. The major cost of maintaining the electrical power system is for scheduled maintenance, which is about the same for both flight phases.

C. DESIGN REQUIREMENTS OF SELECTED TUG SYSTEMS

The results of this study are strongly dependent on the capability of the Tug vehicle to be easily maintained and refurbished. Various assumptions made during the course of the study can be related to design requirements for many of the major vehicle areas. The first and most significant

Table 2. Tug Refurbishment Costs - Percent Per Flight *

	IOC	OC
Basic Structure	0.01	0.01
Meteoroid Shield	0.10	0.10
Tug-P/L Dock.	0.06	0.05
Tug-Shuttle Dock.	0.03	0.03
Propel. Tanks	0.40	0.27
Interface Panels	0.10	0.09
Tank Insulation	0.62	0.46
Main Prop.	0.65	0.34
Aux. Prop.	1.10	0.57
Elect. Power	0.32	0.27
Avionics	0.35	0.18
System Tests	0.17	0.12
TOTAL	3.91	2.49

* Percent of vehicle first unit production cost per flight.

First Unit Hardware Cost

	$ Millions
Structure	2.02
Avionics	3.53
Elect. Power	1.07
Propulsion	3.39
Integration, Assembly, Checkout and Test	0.96
	10.97

assumption made in this study was that the vehicle was designed to be maintained and refurbished. If the costs of maintaining a reusable vehicle like the Tug are to be similar to the estimates made in this study, a design requirement of maintainability and refurbishability must be imposed. This requirement must be imposed at the very beginning of the design phase rather than at some later date in the design as an afterthought. The vehicle must be designed in such a way as to allow components that have limited life and high maintenance requirements to be easily removed and replaced. This must be done with a minimum amount of impact on the remainder of the vehicle.

The results of this study point out the areas which have the greatest effect on the cost of Tug refurbishment. The depth of this study does not permit the identification of specific design requirements; however, this study does identify general requirements that either are necessary if one is to achieve the estimated refurbishment cost estimate or can be a significant factor in reducing the refurbishment cost of the vehicle. The following paragraphs address the five major cost drivers identified for the mature vehicle and attempt to establish some general requirements relative to these systems.

Auxiliary Propulsion System

The auxiliary propulsion system has been identified as the most costly Tug system to maintain. This is due primarily to the complexity and initial cost of the system. The system has certain wearout modes which necessitate the scheduling of replacement maintenance cycles. The ratio of manpower costs to hardware costs for maintaining the system is approximately 13 percent. Therefore, any significant reduction of the cost of maintaining the system must be accomplished via the hardware route. The auxiliary propulsion system is assumed to have a life of 20 missions before major overhaul. After 20 missions, the system is refurbished at a cost of 33 percent of the cost of a new system. The maintenance cost of the system could be reduced by designing for a longer life, designing to a lower refurbishment cost factor, or both. The design life of 20 missions was assumed for this study. The 20 mission life capability of the main engine was used as a guide for this assumption. The 33 percent refurbishment cost factor used for the auxiliary propulsion system was determined by looking at the operations involved and the disposition of the various components removed during the refurbishment of the system.

Two design requirements are apparent for the auxiliary propulsion system as a result of refurbishability and maintainability: (1) the system must have a design life of 20 missions between major overhauls with a design goal of 40 missions, and (2) at the end of the design life the system must be refurbishable at a cost not to exceed 25 percent of the cost of a new unit with a design goal of 15 percent.

Propellant Tank Insulation System

The second most costly item to maintain is the tank insulation system. This is due to the state of development of the system. Currently, the reusability of the system has strong limitations and hence costly replacement and repair maintenance cycles are scheduled. The cost of the maintenance of this system is relatable to the design life of the system. The design requirement for the propellant tank insulation system should be that the system will have a minimum design life of 20 missions before major overhaul with a design goal of 100 missions.

Main Propulsion System

One of the requirements that has been defined for the main engine by the Air Force Rocket Propulsion Laboratory (AFRPL) is that it will have a 10 hour operational life before major overhaul. For the particular missions defined for the Tug, this is equivalent to 20 missions. Also, analytical studies performed by the various engine contractors have indicated that the engine can be refurbished after 10 hours of operation for 25 percent of the cost of a new unit.

This refurbishment study has assumed that the main engine has a 20 mission capability after which it can be refurbished for 25 percent of the cost of a new unit. The capability of a maximum refurbishment cost after 10 hours operation of 25 percent of the cost of a new engine should be made a firm requirement.

Propellant Tanks

The propellant tank life for this study was assumed to be 20 missions after which the tanks were replaced. This assumption results in two design requirements: (1) the tank must be designed for a minimum life of 20 missions with a design goal of 100; and (2) the vehicle must be designed for tank replacement.

Electrical Power

The electrical power system was assumed to have a design life of 2000 hours after which it could be refurbished for 25 percent of the cost of a new unit. The 2000 hour design life is a requirement for a currently funded fuel cell technology study. The refurbishment cost factor of 25 percent is not. The design requirement for the electrical power system resulting from the refurbishment study is that the system have the capability of being refurbished at a minimum cost of 25 percent of a new unit after 2000 hours of operation. The design goal for refurbishment should be 15 percent.

VI. STUDY LIMITATIONS

The task of determining the cost of maintaining and refurbishing a vehicle before that vehicle has been used is a difficult job. The problem of determining these costs for a vehicle such as the Tug that is still in the conceptual phase is even a more formidable one. Without detailed information regarding the design of the various subsystems, any estimate of the refurbishment costs would be mainly conjecture. To help circumvent this problem, a baseline vehicle was synthesized from data obtained from NASA and DOD funded Tug/OOS studies and Aerospace in-house efforts. Each major vehicle system was described and the operations necessary for maintenance of each of the systems were defined. The impact of multiple reuse on the design and operation of spacecraft systems is not well understood. In lieu of an existing data source directly applicable to Tug refurbishment, the experience that has been gained on past and current Air Force space programs was utilized as the main source of information for this study. Many of the systems and subsystems used on these programs, even though they were not designed for reuse, are similar to those that are currently planned for Tug use. Various vendors and manufacturers whose ideas were solicited in regard to the effect of multiple reuse and the cost of refurbishment on their particular equipment were another important source of data. Engineering judgment was used to synthesize these data into a viable approach to Tug refurbishment.

The methods and philosophies used in the maintenance and refurbishment of current reusable vehicles such as commercial and military aircraft are a data base which could be utilized to establish some ideas for the approach to Tug maintenance. However, the differences between these types of vehicles and the Tug in their design and operating modes may not permit a valid comparison of maintenance costs. No attempt was made to compare the study results with the costs associated with maintaining and refurbishing current reusable vehicles.

Vehicle maintenance cost is proportional to the time and effort expended in checkout and testing of the vehicle systems during the post-flight maintenance cycle. Definition of the test points and system self-check capability is a prerequisite for determining the actual effort required to ascertain system status; however, the state of the design of the Tug systems, e.g., the checkout and fault isolation system, does not permit a detailed assessment of the test points and self-check requirements. Hence, some gross assumptions were necessarily made relative to the determination of vehicle status. It was assumed for this study that an on-board checkout and switching system could be developed that could detect all important failures and switch in the redundant component or subsystem. The failure rate of the built-in test equipment (BITE) was assumed to be 10 percent of the total system. The relative complexity of the BITE system and the system being tested was not assessed. No determination of the failure detection probability was made; however, 25 percent was added to all costs associated with random failures to account for false alarms. The redundancy and reliability requirements of the redundancy switching system were not addressed. The results of this study are predicated on the existence of such equipment for redundancy switching and minimizing the amount of ground checkout required between flights. A separate study is needed to define the system that accomplishes this function.

VII. IMPLICATIONS FOR RESEARCH

Several technology requirements have become apparent during the course of the refurbishment study. The first of these pertains to the propellant tank insulation system. The multilayer insulation system is one of the main refurbishment cost drivers mainly because of the unknowns involved with its reuse capability. The current estimate of its reuse capability is that it must be replaced every 5 missions due to deterioration under repeated exposure to the ascent and reentry environment. The technology requirement is to develop more test data on the insulation to gain a better understanding of the effect of repeated exposure to the ascent and reentry environment. This understanding should result in the development of an insulation system that has a life expectancy of 20 missions or more.

The problem of testing the insulation system after each mission has resulted in another technology requirement for the tank insulation system. Multilayer insulation (MLI) must be located in a vacuum environment to perform properly. Generally, space provides the necessary vacuum to permit MLI to perform thermally as it is intended to perform. At sea level conditions, space-evacuated MLI will be filled with air or with a non-condensable gas as a result of purging. In such a condition, the thermal protection afforded by the insulation will be radically reduced. Because of the difference in MLI thermal performance at sea level and high vacuum conditions, there presently is no method to verify MLI space performance without subjecting it to a vacuum test. A method to circumvent this problem is needed. The effort should be directed toward detecting the most common failure modes of the insulation. These are insulation crushing, insulation delamination, joint thermal shorts, etc. Techniques such as X-ray examination may be promising. If testing under ambient ground conditions turns out to be an infeasible method, testing at a moderate vacuum should be investigated.

Several technology requirements have been identified for the successful implementation of large, thin walled propellant tanks for the Tug vehicle. The technology requirements encompass cyclic life considerations, methods of leak checking, and fracture mechanics data characterization.

On the basis of demonstrated cyclic lives of a few hundred cycles for current aerospace thin-walled tanks such as the Titan IIIC Transtage and the Atlas/Centaur, it was concluded that the Tug 20 mission requirement could be met with test and quality control standards similar to procedures used on those programs. Since the Tug tankage is a different material than the materials used on those programs, i.e., aluminum versus titanium (Titan IIIC Transtage) and stainless steel (Atlas/Centaur), a technology requirement is identified consisting of subscale, or full scale Tug tankage subjected to cyclic pressure loading and monitored for leakage. The consideration of tank life extension from 20 missions to 100 missions (200-1000 pressure cycles) also identifies a technology requirement for cyclic pressure testing.

For the routine maintenance of the propellant tanks, a tank leak test with helium was proposed. Although equipment is currently available for such a test, it is necessary to establish a technology requirement to develop small portable devices which could be used conveniently for tank checkout between missions. In addition, the problems associated with detecting helium leakage from tankage covered with thermal insulation should be investigated.

Pressure vessels often contain small flaws, or defects, that are inherent in the materials, or introduced during the fabrication process. These flaws may, in some cases, reduce the load-carrying capability and operational life of the component from the levels predicted by conventional methods of analysis. Fracture mechanics provides a methodology for evaluating the influence of flaws on pressure vessel performance and failure mode. The application of this design method to the Tug tankage is severely hampered by the lack of data for flaws in thin-walled tanks. Therefore, a technology requirement is established for empirical data on pressure vessels with part-through thickness flaws subjected to cyclic pressure. The test program should investigate the cycles to leakage of thin-walled propellant tanks representative of the Tug vehicle due to initial part-through cracks. The program should investigate several aluminum alloys appropriate for cryogenic tankage, several parameters involving flaw geometry (i.e., depth-to-length ratios) and flaw depth-to-tank wall thickness, the influence of temperature, and the influence of tank wall stress levels.

VIII. SUGGESTED ADDITIONAL EFFORT

A. VEHICLE STUDY

The Tug is basically a high performance vehicle that is very sensitive to weight. Historically, vehicles designed for space application have been designed for minimum weight and volume. This has resulted in the development of highly complex mechanical and electrical packaging techniques. For a reusable vehicle, such as the Tug, that must be maintained and refurbished many times, this type of design philosophy is not appropriate. A new design philosophy must be used which stresses ease of maintenance and accessibility to various systems. A vehicle study should be performed to assess the feasibility of such a design philosophy. The vehicle would be designed with the requirement that it be maintainable and refurbishable. Trade studies should be performed to determine the effect on total program cost of varying RDT&E costs and the resultant changes in maintenance and refurbishment costs. The average cost per mission of maintaining this vehicle would then be determined and its performance compared with a Tug that has been designed for maximum performance without regard to maintenance.

B. CHECKOUT AND FAULT ISOLATION SYSTEM DEFINITION

The time consumed and the manpower involved in determining the status of each system before and after each flight is dependent on the amount of ground checkout required. The results of this study are based on the existence of an on-board checkout and switching system that could detect all important failures and switch in the redundant component or subsystem. A study is needed to define the onboard checkout and fault isolation system (COFI). The study should determine the best mix of on-board and ground COFI and operational flight support. Several approaches and their impact on the total vehicle should be examined. The failure rate of the built-in test equipment and the redundancy and reliability requirements of the redundancy switching system should be determined.

C. TOTAL TUG TURNAROUND COSTS

The study reported herein is concerned with only one part of the total Tug turnaround costs, viz., maintenance and refurbishment. Currently, Tug turnaround costs are estimated using cost estimating relationships (CERs) based on experience gained from past programs. A study is needed to develop comprehensive estimates of the costs associated with Tug turnaround from launch to launch based on an assessment of the operations involved as they specifically apply to the Tug. All cost estimates should be developed by assessing the functions, manpower and hardware necessary to support each of the Tug turnaround operations.

D. TUG REFURBISHMENT LOGISTICS CONCEPTS

A study is needed to assess the various approaches to Tug logistics. Various concepts concerning the approach to vehicle maintenance should be identified. The question of who will perform the maintenance and the impact on the total program should be addressed, e.g., private contractor versus the use of a government organization to perform vehicle maintenance. The impact on the funding level and the level of support required at the manufacturer for various approaches to spares support should be identified, i.e., all spares purchased at the beginning of the program or purchased over a longer time span.

APPENDIX A

STUDY 2.4 STATEMENT OF WORK

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2.4 ANALYSIS OF SPACE TUG OPERATING TECHNIQUES

2.4.1 Advanced Tug Program Analysis

The contractor shall define alternative Space Tug configurations. For each, as approved by the Technical Director, the contractor shall identify vehicle system implications and potential programmatic benefits and penalties. Vehicle systems implications shall include vehicle design, performance capabilities, and conduct of ground and orbital operations. The contractor shall include analysis of the impact of the alternative programs on DOD mission and program objectives. In addition, the contractor shall analyze the impact of DOD plans on NASA programs.

Task areas shall be identified by the contractor and when approved by the Technical Director, in depth studies shall be conducted. Typical of the types of studies are retrieval mechanisms and techniques, on-orbit stay time requirements, ground and vehicle command and control techniques, definition of a Mark I and Mark II Tug subsystem technology, licensee considerations, and assessment of technology requirements.

2.4.2 Tug Checkout, Maintenance, and Operational Readiness Preparation

Background:

The contractor has, in support of prior DOD/NASA activity, analyzed orbital checkout, maintenance, and operational readiness activities applicable to candidate Space Tug configurations and will further develop these activities. Vehicle-peculiar design requirements will be identified and optimum levels of test maintenance and refurbishment recommended. The study should consider diagnostics, maintenance and repair, assembly and refurbishment, and checkout. In addition, the study will address the requirements and techniques for on-orbit checkout of the Tug prior to deployment.

The objective of this task is to develop a better understanding of the refurbishment requirements and operating life for typical Space Tug concepts and their constituent subsystems/components, and the relationship between these factors and Tug design, weights, and costs. This set of information will be used in examinations and selection of design approaches and operating approaches for the Space Tug.

The contractor shall provide:

(1) For a typical Space Tug or Orbit-to-Orbit Shuttle concept, develop and compile detailed estimates for the following for each of the constituent subsystems/components and for the composite Tug.

(a) The extent of servicing, adjustments, checks, and replacements to be necessary following each flight.

(b) Major repairs and/or replacements that will be necessary at regular intervals, or upon indication of performance reduction or incipient failure.

(c) The operating life to be expected prior to reaching the point that replacement of the Tug would be more practical or economically attractive, in lieu of continued refurbishing and overhaul.

(d) Man-hour and cost estimates for the preceding.

(2) Description of maintenance/refurbishment approach and procedures upon which the preceding man-hour/cost estimates are based.

(3) As an extension of the foregoing analyses of a "typical" or "baseline" Space Tug concept and configuration, the following should be developed.

(a) Recommended design features or approaches for Space Tug including consideration of associated ground equipment which would reduce or minimize Tug refurbish/overhaul requirements.

(b) The approximate relationships between refurbish/overhaul requirements and Space Tug design, weights, and development/unit costs, where the Tug design or development is varied to achieve a different refurbishment overhaul level.

(c) The effect of the baseline refurbish/overhaul/life estimates upon total Tug program costs, and the sensitivity of operating and program costs to variations in these estimates.

The basic approach for this study and the major assumptions to be used should be reviewed by the Technical Director.

2.4.3 Future Requirements

New requirements brought about by reusability as a standard mode of operation shall be identified and recommendations for future studies shall be made. Examples include (a) technology improvements needed to assure sufficient on-orbit capabilities, (b) demonstration or verification experiments for application to Skylab or early Space Shuttle missions, and (c) study the tradeoff considerations of the Tug and Shuttle interface considering requirements imposed on the Shuttle or Tug, as compared to providing a separate interfacing module to be used on Shuttle flights requiring a Tug.